DIRECT MEASUREMENTS OF TOTAL REACTION CROSS SECTIONS BETWEEN HEAVY IONS FROM 10 TO 100 MeV/amu: PRELIMINARY CONCLUSIONS

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DIRECT MEASUREMENTS OF TOTAL REACTION CROSS SECTIONS BETWEEN HEAVY IONS FROM 10 TO 100 MeV/amu : PRELIMINARY CONCLUSIONS

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Résumé - Après une revue des principales formulations théoriques du concept de section efficace totale de réaction σ_R développées d'une part pour les collisions à basse énergie ($\lesssim$ 10 MeV/nucléon) et d'autre part, pour les collisions à haute énergie ($\sim$GeV/nucléon), deux méthodes de mesure directe de σ_R sont brièvement présentées (la méthode dite de transmission et la méthode du rayonnement associé). Les résultats expérimentaux obtenus depuis 1982 dans la gamme d'énergie incidente de 10 à 100 MeV/nucléon sont interprétés dans le cadre de deux approches théoriques différentes : l'une basée sur l'intéraction potentielle Noyau-Noyau (modèle macroscopique "basse énergie"), l'autre sur les intéractions individuelles nucléon-nucléon (modèle microscopique "haute énergie"). Divers problèmes expérimentaux et théoriques relatifs à l'observable σ_R sont discutés et quelques conclusions générales sont alors avancées. Le domaine de l'énergie de Fermi apparaît, à travers l'étude des sections efficaces totales de réaction, comme étant un bon domaine pour affiner nos concepts et nos interprétations de la vraie nature du noyau atomique.

Abstract - After a review of some theoretical formulations of the concept of total reaction cross σ_R, involving low energy ($\lesssim$ 10 MeV/amu) and high energy (> GeV/amu) models, two experimental methods used for direct measurements of σ_R, are presented, namely the "beam attenuation" and the "associated γ-rays 4 π detection" methods. Then a number of experimental results of σ_R in the Fermi energy range is given and the data are compared on the one hand with the predictions of the "low energy" BASS model (assuming a classical one-dimensional nucleus-nucleus potential interaction), and on the other hand with the predictions of a "high-energy" microscopic calculation performed using the formalism of KAROL (assuming that nuclear reactions are produced by individual nucleon-nucleon interactions). Finally, some experimental and theoretical problems are discussed and general conclusions are tentatively proposed.

I - INTRODUCTION

For many years heavy-ion total reaction cross sections σ_R have been widely measured at low energies ($\lesssim$ 10 MeV/amu), σ_R being generally identified either with the fusion reaction cross section σ_F (see, for example, measurements of σ_F by direct observation of heavy recoil nuclei in bombarding different targets with a ^{32}S beam /1/), or with the total cross section for production of fission fragments σ_{FF} (see, for example, experiments in which ^{238}U target was bombarded with various projectiles /2/).

In contrast, in the Fermi energy domain, there are until now only some pioneering data obtained in the last few years. The aim of this paper is to attempt to a synthesis of almost recent results essentially concerned with direct measurements of σ_R in the 10-100 MeV/amu incident energy range. The main sources of experimental data are provided by the works of the groups mentionned in references /3,4,5/.

The total reaction cross section is one of the most fundamental quantities characterizing nuclear reactions; it is also one of the oldest concepts in Nuclear Physics..that is a very good reason for not neglecting to recall and discuss, as accurately as possible,basic ideas and definitions relevant to the interaction probability of two colliding nuclei.

II - THE BASIC FEATURES OF THE TOTAL REACTION CROSS SECTION

II-1 The classical geometric concept of σ_R

Two basic characteristics of nuclei have to be taken into account to define a measure of the nuclear reaction probability : one is the nucleus charge which induces a Coulomb trajectory effect, and the other is the spatial nucleon density distribution the knowledge of which is fundamental to correctly express the rate of nuclear reactions.

Elementary concept of total reaction cross section σ_R is illustrated on the figure 1 which emphasizes the effect of the Coulomb repulsion in reducing the σ_R value, and recalls the central role played by the basic parameter R_{int}, referred to as the "(effective) interaction distance" which separates the domains of elastic scattering and nuclear reaction in configuration space. For a given value of R_{int}, we can write the well known classical expression of σ_R :

$$\sigma_R = \pi b_{max}^2 = \pi R_{int}^2 \left[1 - V(R_{int})/E_{CM}\right] \qquad [1]$$

which is obtained from the conservation of angular momentum and energy along a classical trajectory. In this relationship, $V(R_{int})$ denotes the potential energy (Coulomb V_C + nuclear V_N) at the interaction distance, and E_{CM} the total kinetic energy in the center-of-mass system.

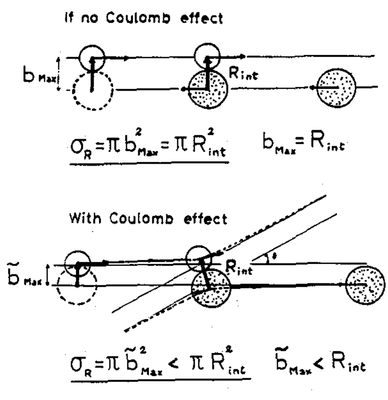


Fig. 1 Coulomb effect acts to decrease σ_R

In order to specify the importance of the Coulomb repulsion in the Fermi energy domain, we present in figure 2 some rough calculations of $(\pi R_{int}^2 - \sigma_R)/\pi R_{int}^2$ and $(R_{int} - b_{max})$ for the colliding systems ^{20}Ne and ^{40}Ca on ^{64}Zn and ^{208}Pb, assuming :

- an energy independent interaction distance, namely with $R_0 = 1.4$ fm :

$$R_{int} = R_0 \left(A_p^{1/3} + A_t^{1/3}\right) \qquad [2]$$

(that is the crude approximation of the black disk model)

- a nuclear potential contribution $V_N(R_{int}) = 0$ so that

$$V(R_{int}) = V_C(R_{int}) = Z_p Z_t e^2/R_{int}$$

It is clear that in most cases Coulomb effect must be correctly evaluated particulary for heavy systems.

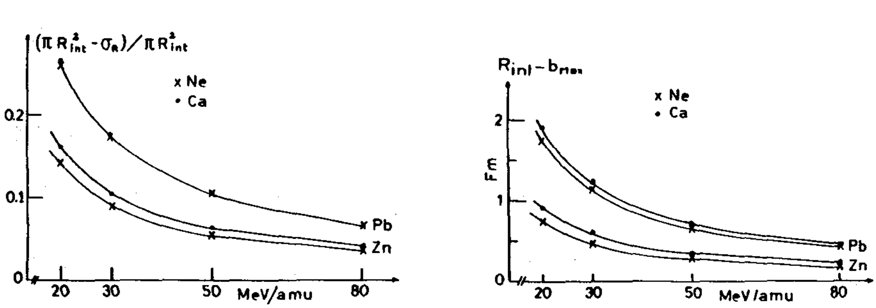


Fig. 2 Assessments of Coulomb effect

The crude geometrical expression $\sigma_R = \pi b^2_{max}$ may be related to a more refined formulation based on the usual summation of partial (waves) cross sections :

$$\sigma_R = \pi \lambda\!\!\!^{-2} \sum_0^{\infty} (2\ell+1) \widetilde{T}_\ell \qquad [3]$$

where $\widetilde{T}_\ell$ is the transmission coefficient for the ℓ-wave. In practice there will be a transition region in angular momentum space where the transmission coefficient varies smoothly form near-unity to pratically zero. In a sharp cut-off model a step function is used for the decrease of $\widetilde{T}_\ell$ from 1 to 0 at a cut-off value ℓ_{max} ($\widetilde{T}_\ell = 1$ means that a reaction occurs) and we can write :

$$\sigma_R = \pi \lambda\!\!\!^{-2} (\ell_{max} + 1)^2 \qquad [4]$$

For large values of ℓ_{max}, using the semi-classical relationship $\ell\lambda\!\!\!^{-} \simeq b$, we find the crude expression $\sigma_R = \pi b^2_{max}$. Since very many partial waves contribute to a heavy-ion reaction it may be convenient to replace the summation by an integral so that σ_R can also be expressed as:

$$\sigma_R = 2\pi \lambda\!\!\!^{-2} \int_0^{\infty} \ell \widetilde{T}(\ell)\, d\ell = 2\pi \int_0^{\infty} b\, \widetilde{T}(b)\, db \qquad [5]$$

the transmission coefficient $\widetilde{T}_\ell$ being replaced by a transmission function $\widetilde{T}(\ell)$ or $\widetilde{T}(b)$. The sharp cut-off approximation thus yields to the relations :

$$\sigma_R = 2\pi \lambda\!\!\!^{-2} \int_0^{\ell_{max}} \ell d\ell = \pi \lambda\!\!\!^{-2} \ell^2_{max} = 2\pi \int_0^{b_{max}} b db = \pi b^2_{max}$$

The limiting angular momentum $\ell_{max} = (1/\lambda\!\!\!^{-}) b_{max}$ is related to R_{int} and E_{CM} through the relation [1] which in fact is directly derived from the energy conservation equation $E_{CM} = (h^2/2\mu R^2_{int})\, \ell^2_{max} + V(R_{int})$. The partial waves formulation of σ_R points out the important contribution to σ_R of the various peripheral-type reactions, and emphasizes that a good description of the total reaction cross section needs a well-suited accoun of the nuclear surface properties. At this point let us recall that in its strict sense σ_R is defined as the sum of all non-elastic nuclear reaction channels.

Now we have to give a more precise formulation of the interaction distance R_{int}. This distance must be expressed as a function of the radii of projectile and target nuclei, remembering that the spatial distribution of proton and neutron in the nucleus has a strong influence on the rate of nuclear reaction. We then get in the maze ([1]) of the nuclear radii definitions and analytical expressions /6,7,8/ (in addition to the semantic ambiguity "radius/distance" to describe the interaction of two nuclei). Futhermore it is now well established /9/ that, at least for the medium weight and heavy nuclei, the neutron distribution extend slightly beyond the proton distribution. Presently neglicting this fact (we should come back to this question in the last chapter) we give in figure 3 a schematic illustration of the overlap of the matter density distributions of projectile (p) and target (t) nuclei at the interaction distance R_{int} , expressed as being approximately 3 fm larger than the half-density distance $R_{1/2}$ (p-t) = $R_{1/2}$ (p) + $R_{1/2}$ (t) between the two nuclei

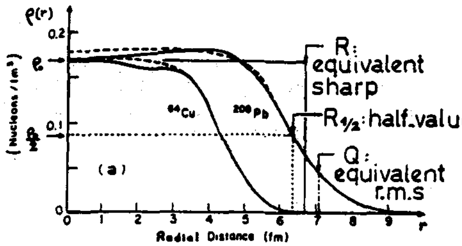
$$R_{int} \simeq \{R_{1/2}(p) + R_{1/2}(t) + 3\} \text{ fm} \qquad [6]$$

A rough usual expression of the half matter density radius for a nucleus of atomic mass number A is :

$$R_{1/2} = r_o A^{1/3} = 1.1\, A^{1/3} \text{ fm} \qquad [7]$$

The formulation [6] of R_{int} provides a more useful representation of the interaction distance than the conventionnal parametrization [2] where the "radius parameter" R_o varies systematically with target and projectile masses.

([1]) Central radius; (effective) half (value) (density) (matter) (charge) radius; root mean square radius; sharp (surface) radius; effective nuclear radius; strong interaction radius, and so on... the reader will complete the list !



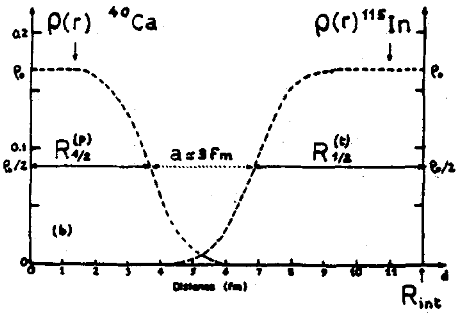


Fig. 3 - (a) Experimental (solid line) matter density distribution and theoretical (dashed line) Fermi I distribution function. Radii definitions are those of reference/6/

(b) Matter density overlap of the two colliding nuclei ^{40}Ca + ^{115}In at the interaction distance $R_{int} = R_{1/2}$ (^{40}Ca) + $R_{1/2}$(^{115}In) + 3 fm

It is noticeable that such a classical analysis of σ_R so far disregards nuclear deformation : it is postulated that all the parameters involved in the σ_R expression have and keep at the time of the collision a spherical symmetry (e.g. V(r), ρ(r)...). Obviously it is allowed to think that dynamical nuclear deformations (dependent on impact parameter) may, in some cases, significantly perturb this symmetry. However it is assumed in first approximation that in the Fermi energy range this has a small repercussion on the <u>total</u> reaction cross section.

II-2-Nuclear transparency effect

For many years it is experimentally established /10,11,12/ that, for reactions induced by light projectiles (such as n,p,d,α) at energies from several ten to several hundred MeV/amu there are strong deviations of the measured σ_R from the classical expression $\sigma_R = \pi R_{int}^2\,[1 - V/E_{CM}]$. The total reaction cross section does not "saturate" to the geometric values πR_{int}^2 as increasing the bombarding energy : instead, after peaking at a few tens of MeV/amu, the values of σ_R decrease steadily until after 100 MeV/amu is reached. Such observations have also been reported for relativistic heavy ions collisions /13/. This fall-off of σ_R as a function of the energy is referred to as a <u>nuclear transparency</u>. This nuclear transparency effect may be included in previously proposed classical formulations of σ_R.

A first way is to modify the standard expression $\sigma_R = \pi R_{int}^2\,[1 - (V_C+V_N)/E_{CM}]$ by writting

$$\sigma_R = \pi R_{eff}^2\,[1 - V_C/E_{CM}]\,[1-T] \qquad [8]$$

where <u>T is a global transparency parameter</u> varying as a function of the projectile energy and R_{eff} an effective interaction distance taking into account the nuclear potential effect at low incident energy. This approach has originally been developped for nucleon induced reactions by BETHE /14/ in the form :

$$\sigma_R = \pi R^2\,[1-T] = \pi(r_o A^{1/3})^2\,[1-T]$$

and then refined by RENBERG et al. /11/ with the modified formula :

$$\sigma_R = \pi(R+\lambda\!\!\!^-)^2\,[1-Z_pZ_te^2/(R+\lambda\!\!\!^-)E_{CM}]\,[1-T] \qquad [9]$$

in which $R+\lambda\!\!\!^- = r_oA_t^{1/3} + \lambda\!\!\!^-$ (with r_o = 1.3 fm) is the effective interaction distance and $\lambda\!\!\!^-$ the reduced wavelength of the incident particle. The transparency T is considered to be a nuclear property, in the sense it is related to an absorption coefficient.

which is the reciprocal of the mean free path of the incident nucleon in nuclear matter. The formulations [8] and [9] consist in fact in reducing the interaction distance when increasing energy. An interesting conclusion of RENBERG et al. /11/ is that the transparency is seen to decrease with increasing target mass number, i.e. the reaction cross section comes closer and closer to the geometrical cross section. For relativistic heavy ion collisions a rough parametrisation has been very early proposed /15/ referred to as the overlap model : $\sigma_R = \pi[R_0(A_p^{1/3} + A_t^{1/3}) - \Delta R]^2$ where ΔR is the overlap term (of the order of magnitude of nuclear force range).

An other way of taking transparency effect into account is to start with the expression [5] and then to express the transmission function $\tilde{T}(b)$ in the form $\tilde{T}(b) = [1 - T(b)]$ where T(b) is the so-called transparency function, which represents the probability that at impact parameter b the projectile will pass through the target without interacting, so that :

$$\sigma_R = 2\pi \int_0^\infty b[1 - T(b)]\, db \qquad [10]$$

The theoretical calculation of σ_R is thus reduced to the problem of calculating T(b), which can be achieved in microscopic way assuming that nucleus-nucleus interactions result from single nucleon-nucleon collisions in the region of overlap between projectile and target. Some of the basic features of such interpretation of σ_R(mean free path Λ of nucleon in nuclear matter; nucleon-nucleon total cross sections; effect of the Pauli exclusion principle on the scattering by a nucleon bound in the nucleus) have early (1949) been mentioned by FERNBACH et al./10/ who have explained transparency observed in high energy neutron-nucleus collisions. Later, an analytical formulation of a σ_R microscopic calculation, according to [10] , has been proposed by KAROL/13/ for high energy (GeV/amu) heavy ions collisions : in this geometrical model, trajectory Coulomb and nuclear effects are ignored (straight line path of colliding nuclei) as are considerations of Fermi motion of nucleons within nuclei and Pauli Blocking effect (effect of the exclusion principle on the nucleon-nucleon scattering cross section inside nuclei), but the calculation of T(b) includes realistic matter density distribution ρ (Gaussian functions are used for the whole distribution of light nuclei and for the tail of distribution for heavy nuclei). The way on which the calculation is performed may be very briefly summarized as follow : the local mean free path of the projectile moving in the z axis direction at impact parameter b is defined as

$$\Lambda(b,z) = \left[\overline{\sigma_T^{NN}} \cdot \tilde{\rho}_{pt}(b,z)\right]^{-1} \qquad [11]$$

- $\tilde{\rho}_{pt}(b,z)$ is the target-projectile overlap matter density (folding of the target ρ_p and projectile ρ_t densities)

- $\overline{\sigma_T^{NN}} = \left[(Z_pZ_t + N_pN_t)\, \sigma_T^{pp} + (Z_pN_t + N_pZ_t)\, \sigma_T^{pn}\right]/A_p.A_t$ is the spin-isospin average nucleon-nucleon total cross section

- $\sigma_T^{pp} = \sigma_T^{nn} \neq \sigma_T^{pn} = \sigma_T^{np}$ are the experimental (free diffusion) nucleon-nucleon total cross sections /16/.Then the probability T(b) that the projectile undergoes no interaction at impact parameter b is given by :

$$T(b) = \exp\left(- \int_{-\infty}^{+\infty} \frac{dz}{\Lambda(b,z)}\right) \qquad [12]$$

The dependence of T(b) (see fig. 4)-and thus of σ_R - on projectile energy is determined by the energy dependence of the $\overline{\sigma_T^{NN}}$(see fig. 5)

In this formulation it is assumed that the outgoing flux in the inelastic channels occurs by means of nucleon-nucleon collisions : only one nucleon-nucleon collision is enough to have a nuclear reaction event contributing to σ_R. With equivalent high energy approximations as those of the KAROL model, but describing the scattering by a first order optical potential in the impulse approximation, ERNST /19/ has fairly well reproduced σ_R experimental data for proton-nucleus collisions in the energy range 100 MeV - 1 GeV.

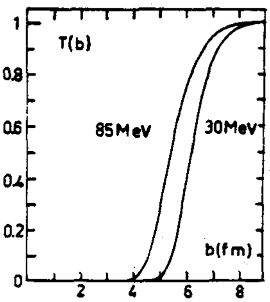


Fig. 4 - $^{12}C + {}^{12}C$ transparency function T(b) (from Ref. /17/)

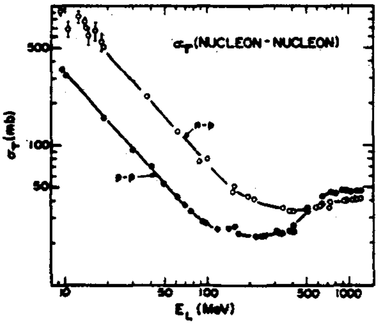


Fig. 5 Nucleon-nucleon total cross-sections as a function of incident lab. energy (from Ref/18/)

It must be mentioned that, although the KAROL's calculation is essentially geometric, the deduced final formulation of σ_R is equivalent/17/ to the optical limit of the GLAUBER theory /20, 21/. In this theoretical framework, high energy collisions between heavy nuclei have been extensively studied by FRANCO /22/, and calculations of nucleus-nucleus σ_R in the Fermi energy domain (taking into account Coulomb effects) have been performed by DEVRIES et al /18, 23/.

But the optical limit of the GLAUBER theory ignores Pauli blocking as well as the Fermi motion of the nucleons : the formalism has thus been refined by DiGIACOMO, DeVRIES and PENG /24/ by including the effects of the Coulomb potential, real nuclear potential, Pauli blocking and Fermi motion, providing a good description of the data for nucleon-nucleus collisions in a broad range of energy (15 MeV through 1 GeV). An effective nucleon-nucleon total cross section in nuclear matter (Fermi and Pauli effects) must be used : the figure 6 illustrates the variations of the effective proton-proton σ_T^{pp} (bound) as a function of the relative momentum of the incident proton and the target nucleus (K_F is the radius of the Fermi sphere describing the target nucleus in the momentum space). Calculations of effective σ_T^{NN} in the case of nucleus-nucleus collisions have also been performed by DIGIACOMO et al. /25/ in a geometrical model. More recently TREFZ et al. /26, 27/ have proposed a very elaborated microscopic parameter-free calculation of the heavy-ion optical potential, built from the basic effective nucleon-nucleon interaction. This model (Cf. FAESSLER's talk, this conference) provides a good description of heavy-ion σ_R data in the Fermi energy range.

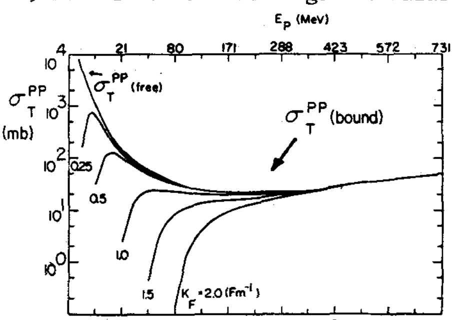


Fig. 6 - Calculated effective proton-proton total cross section in nuclear matter (from Ref. /24/)

In summary, the various microscopic approaches above-mentioned are more or less based on high energy approximations and it follows that nuclear transparency is linked to the energy dependence of the underlying nucleon-nucleon interaction. The level of sophistication of calculations varies with the energy range and mass domain they are supposed to describe. At low energy ($\lesssim$ 10 MeV/amu) the crude use of σ_T^{NN} (free) is a priori not justified and it seems very reasonable to allow (in addition to Coulomb effect) for nuclear "mean-field" effects such as real nuclear potential (trajectory effect increasing σ_R at low energy), Fermi motion,and Pauli blocking (nucleonic collision inhibition effect decreasing σ_T^{NN}). A very schematic and greatly idealized exhibition of basic parameters governing the evolution of σ_R as a function of the collision energy is given in figure 7 : the tendancy of the attractive real nuclear potential to increase σ_R is due /28/ to the deflection into regions of higher target density, to the increase of the relative velocity at which the nucleon-nucleon collision occurs, and to the increase of the path length within the target.

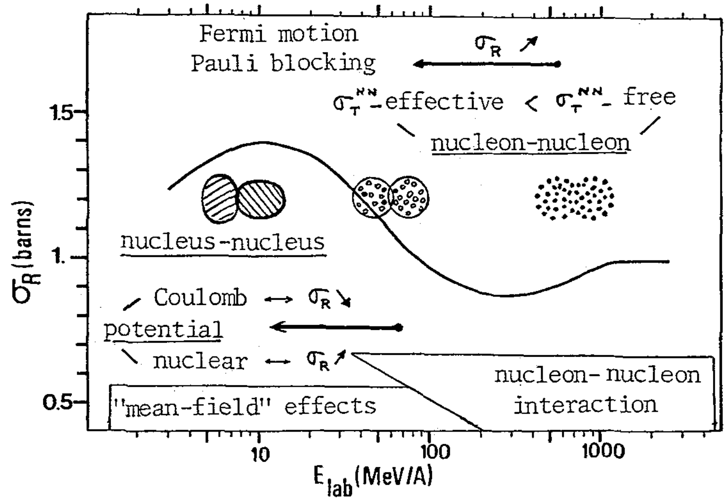


Fig. 7 - The three ways two pieces of nuclear matter make acquaintance

III - EXPERIMENTS IN THE FERMI ENERGY DOMAIN AND THEORETICAL INTERPRETATION OF RESULTS

III-1-Motivations to undertake σ_R measurements in the Fermi energy domain

As emphasized in the previous chapter, following the rather refined theoretical work of DiGIACOMO . DeVRIES and PENG /12,18,20,21/, who have succeeded in describing σ_R for nucleon-nucleus collisions in the 10-1000 MeV/amu range, the question is asked to know to what extent σ_R values for heavy-ion collisions may be explained in terms of individual nucleon-nucleon interactions. Such a question is particulary pertinent in the Fermi energy domain (transition domain between low ang high energy for the physics of the nucleus in colliding situation). This question may be extended to the more general problem of mechanism reaction analysis : is the interaction between two complex nuclei simply the incoherent superposition of individual nucleon-nucleon interactions or are there cooperative effects such as nucleon-nucleus or nucleus-nucleus interactions that are qualitatively different ? However, with regard to σ_R, it is important to realize that the problem is not to describe the dynamical evolution of the collision (that would be necessary to perform the calculation of a partial cross section relevant to a specified reaction mechanism) but simply to describe the initiation of any reaction. So, the question must be addressed in a more precise formulation : to what extent, in the Fermi energy domain, the initiation of a nuclear reaction may be governed by incoherent individual nucleon-nucleon collisions or by "mean field" interaction, keeping in mind the fundamental role played by the nuclear surface (i.e by the tails of nucleonic distributions). Obviously, a pragmatic motivation to measure heavy-ion σ_R in the 10 - 100 MeV/amu range, is also the current increasing of experiments in this realm.

III - 2-Direct measurements of σ_R

Values of σ_R may be extracted from elastic scattering data but they are then to some extent model dependent. It is therefore considered worthwile to obtain direct measurements. Two complementary methods of direct measurement (having in common the fact that they involve *multi-counters detection*) have been recently used /3,4,5/ : they are briefly described here and the main results obtained in this way for heavy-ion collisions in the Fermi energy range are presented.

III-2-1-Measurements using the attenuation method

This method /29/, the up-to-date version /3/ of which is shown schematically in Fig. 8, consists in measuring, for a given number N_B of incident beam particles, the number N_T of beam and elastically scattered particles after passage through the target. The difference between this two numbers is directly proportionnal to σ_R : $\sigma_R = K\ (N_B - N_T)/N_B$ where K accounts for the target thickness. The counting of N_B ($\sim 5.10^4$ particles/s) is provided by the thin scintillator counter "1" anticoinciding with the active collimator "2" (referred to as $B = 1.\bar{2}$). The particles after the target must be not only counted but also characterized in order to discriminate the non-reacting particles against the reaction products. This is achived by the means of a "wheel" arrangement (cylindrical symmetry around the beam axis) of 19 thin ΔE plastic scintillators, each of them furnishing a ΔLight signal (charge and energy dependent) and allowing a time-of-flight measurement with respect to the counter "1". An identification is made by using the two-dimensionnal plot ΔL - t : the charge identification of light heavy-ion projectile ($Z \lesssim 10$) is quite good but the separation of inelastic scattering and neutron-transfer reaction from elastic scattering is not always unambiguous and corrections have to be included in the extraction of σ_R values. The central detector "3" sees the direct beam, the major part of elastic events, and some reaction products : in first approximation this detector gives the number N_T previously defined [N("3") $\approx N_T$], and the difference $N_B - N_T$ may be electronically built by means of the anticoincidence [$B.\bar{3}$]. Target-in/target-out measurements are necessary to correct for reactions induced in counters "1" and "3", so that a first raw determination of σ_R is given by $\sigma_R = K..$ [$B.\bar{3}$ (target in) - $B.\bar{3}$ (target out)]. Then, various corrections must be included in the final determination of σ_R. Target reaction products detected in counter "3" must be substracted, and elastic events detected in the counters mosaic surrounding the central "3" scintillator must be added (after evaluation of inelastic scattering and neutron-transfer). Other corrections due to the geometry of the apparatus must also be taken into account : the elastic scattering outside the cone covered by the detector arrangement and the loss of elastic events in the inefficient detection regions corresponding to the mechanical support of the scintillators (these corrections are the most important ones when Z(target) > 30). A more detailed discussion of the experimental setup performances may be found in the KOX's thesis /30/. The attenuation method is particularly well-suited to measure σ_R of light heavy-ion collisions : the algebraic sum of the various corrections to raw measurements remain generally less than 15% of σ_R and the associated uncertainties contribute about 40% of the final error on σ_R.

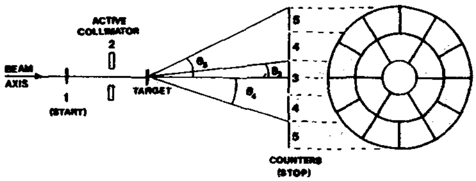


Fig. 8 - Schematic of the experimental setup used in the attenuation method (from Ref. /3/)

Experiments using this apparatus have been performed with the ^{12}C beam (83 MeV/amu) of the synchrocyclotron at CERN, and with ^{12}C and ^{20}Ne beams delivered by the SARA facility (30 MeV/amu) or the SATURNE facility (between 100 and 300 MeV/amu) /3,5,31/. Such a systematic study of σ_R as a function of the energy clearly points out the transparency phenomena in the Fermi energy range for light heavy-ion collisions (see Fig. 9)

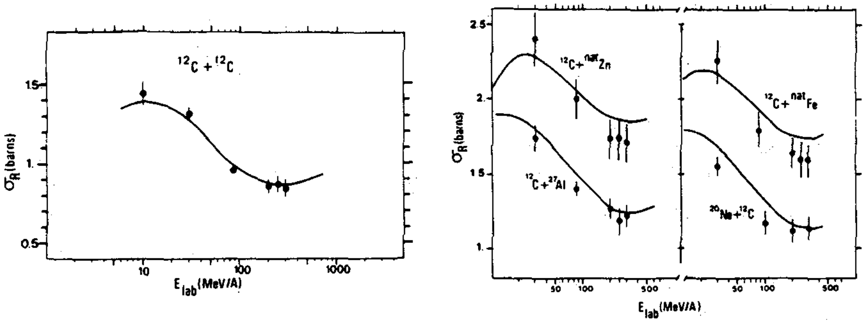


Fig. 9 - Variations of σ_R as a function of the projectile energy. The full curves represent microscopic calculations (From Ref. /5/)

III-2-2-Measurements using the associated γ-rays 4 π detection

Direct measurements of σ_R can be achieved in principle by integrating over the yields of all possible reaction products : in the radiative detection method using a 4 π NaI detector, heavy-ion collisions events are characterized by the observation of the induced γ-ray transitions (moreover some additional light particles as neutrons or energetic protons can be detected). The basic assumption of this method /4,32/ is that each nuclear reaction (obviously scattering process excluded) is necessarily followed by the emission of at least one γ-ray (or one detectable energetic light particle). The GANIL γ-ray modular sum spectrometer has been used as 4 π detector in the experimental setup schematically described in Fig. 10. The detector assembly is built-up from 14 separate large volume NaI counters surrounding the target in an approximately 4 π geometry. (Total solid angle $\Omega/4\pi$ = 0.93). The efficiencies ε for ^{137}Cs γ-ray (0,66 MeV) and ^{60}Co γ-rays (1,17 MeV and 1,33 MeV) are respectively 0.8 and 0.9. The detection probability of a reaction involving M γ-rays can be expressed as $P_M = 1 - [1 - \varepsilon]^M$, which for ε = 0.8 (i.e assuming $E_\gamma \cong 0.7$ MeV) leads to P_2 = 0.96 and P_3 = 0.99.

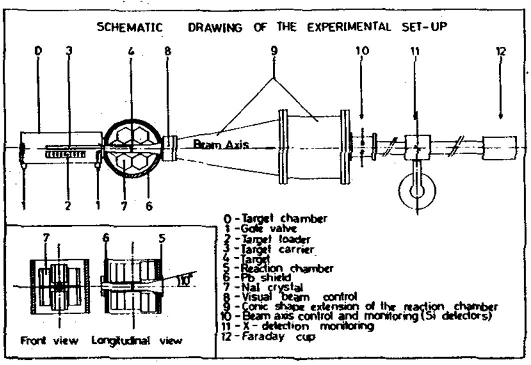


Fig. 10 - 4 $\pi\gamma$ experimental setup

There are three kinds of γ-rays : the good one "G", the bad one "B" and the forged one "F". The "G" are the prompt γ-rays issued from the target : they are time-correlated with beam bursts and detected in coincidence with the accelerator RF signal. The "B" have several origins : (a) residual radioactivity in the target (small contribution when rather thin targets are used, i.e. ~1 mg/cm^2) - (b) various room backgrounds, a drastic attenuation of which was performed by low activity lead shielding of the NaI counters - (c) proper activity of NaI material induced by light particles reactions... it is recommanded not to send the beam outside the target ! -(d) γ-rays from secondary reactions induced by elastically scattered projectiles interacting with the chamber material. In order to distinguish these γ-rays from the target-reaction's γ-rays, the design of the reaction chamber includes a conic exit extension (opening half-angle $\Theta \simeq 10°$, length $\simeq$ 2 m) in such a way that the major part of secondary reaction γ-rays sources are space and time "delocated" : the detection of secondary reaction γ-rays is time-moved with respect to that of the prompt target γ-rays and performed with a highly reduced efficiency. The "F" are due to pile-up of X rays produced in atomic collisions between projectiles and target atoms, the cross sections of which may reach some 10^4 barns : these X-rays were conveniently absorbed by means of Cd foils surrounding the reaction chamber. It is essential to note that this method is based on a single type detection of unidentified γ-rays (except the time discrimination using the RF signal). It thus implies the use of a low intensity ($< 10^8$ p/s) but high-quality beam (small emittance, good stability) and the need for a permanent checkup of the beam alignment (equalization of counting rates of four Si (Li) detectors, symmetrically mounted around the beam axis). Obviously target-in/target-out measurements were also performed in order to verify that the size of the beam and the level of the background radioactivity were quite acceptable. Three types of beam monitoring were used : the Faraday cup beam charge integration, the Rutherford scattering measurements and a relative monitoring based on the detection of K X-rays from atomic collisions induced by the beam on a gold foil (positioned nearby the entrance of the Faraday cup). The consistency of these three monitorings was required to valid a measurement of σ_R.

The availability of a 4 π multidetector counter greatly renewes the radiative methods of cross section measurements /33/ : detection efficiency is a small source of error, dead time corrections may be avoided, and selection conditions on the multiplicity ("folds") may be used.

The principal contributions to the final error on σ_R ($\cong$ 10%) are the uncertainties on target thickness and beam dose determinations. Moreover it must be mentioned that the experimental σ_R values resulting from radiative measurements include the contribution of Coulomb excitation which has to be considered as a systematic error. This contribution however do not exceed few percent of σ_R at incident projectile energy of several tens of MeV/amu (a calculation performed with the code ECIS, for the 44 MeV/amu ^{40}Ar + ^{208}Pb system, gives σ(Coulex) $\cong$ 1% of σ_R /34/) and thus is within the data associated uncertainties. Such a problem has been discussed by OESCHLER et al. /35/ about the determination of σ_R from elastic scattering data when Coulomb excitation is important.

Experiments using the above described setup have been performed with a ^{20}Ne beam (30 MeV/amu) from the SARA facility and with the ^{40}Ar (44 MeV/amu) and ^{40}Ca (77 MeV/amu) beams provides by the GANIL accelerator. The aim was to get a first quite large sampling of σ_R values, in the Fermi energy domain, for medium-light projectiles and a wide range of target masses. Such direct measurements (which are a matter for the radiative method) are not intended to provide an experimental illustration of nuclear transparency but rather to furnish a preliminary database in order to test various theoretical predictions. Some resulting values of σ_R are displayed in Fig. 11, with their corresponding errors bars, as a function of R^2_{int} as defined by formula [6] .

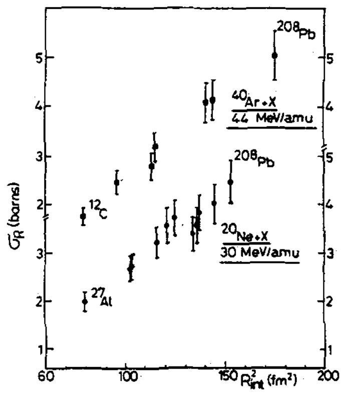


Fig. 11 - Plots of σ_R values as a function of R^2_{int}

It will be noted that σ_R results obtained from the radiative method for Ne induced reactions are in excellent agreement with the data obtained from the beam attenuation method for light and medium-light targets.

III-3-Data analysis and discussion

There are two kinds of theoretical formulations of σ_R which are basically different. One is the "low energy" standard theory based on the one-dimensional interaction potential between two spherical nuclei : the BASS model /7/ which provides a simple analytical formula belongs to this category. Another is the "high energy" microscopic theory based on the indididual nucleon-nucleon collisions in the overlap volume of the two colliding nuclei : the KAROL's analytical formulation /13/ is probably the simplest realistic formulation belonging to this second category. At intermediate energy it is, a priori, very lilely that individual nucleon-nucleon interactions are competing with mean-field effects. To evaluate the degree of this competition, it may be interesting to first consider the "degree of (disagreement", with experimental data, of the straight formulations of "nucleus-nucleus" and "nucleon-nucleon" models. Next, the usefulness of a refined mixture of this two approaches can be discussed (any nuclear reaction starts with a nucleon-nucleon collision).

The energy dependence of σ_R data for light colliding systems (see fig. 9) bears striking ressemblance to that of the σ_T^{NN} data shown in fig. 5. This observation strongly suggests an interpretation of the nucleus-nucleus total reaction cross section in terms of individual nucleon-nucleon collisions. The KAROL formulation was used /5,31/, slightly modified in order to take into account the trajectory Coulomb effect which is not inconsiderable at medium energy : in formula [10] T(b') is substituted for T(b) with b' being the classical distance of closet approach corresponding to the (asymptotic) impact parameter b. Agreement with experimental data is quite good for light systems $^{12}C + ^{12}C$ or ^{27}Al, and reasonably meaningful for the medium-light systems (see fig.9 and 12). It must be mentioned that calculations of PENG et al /23/ for $^{12}C + ^{12}C$ reaction also give a successful description of the $\sigma_R(E)$ data. Moreover a new semi-empirical parametrization formula of σ_R has been proposed by Kox et al /31/, which gives good predictions (within a precision of about 10%) in the Fermi energy range for ^{12}C, ^{20}Ne and ^{40}Ar induced reactions. This formula is in fact an elaborated expression of the overlap model /15/, including mass asymmetry and energy dependent transparency terms.

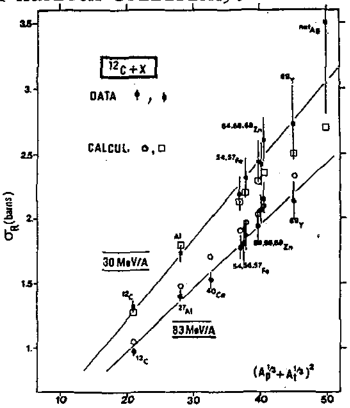


Fig. 12 - Experimental σ_R data and KAROL's calculations (from Ref./30/)

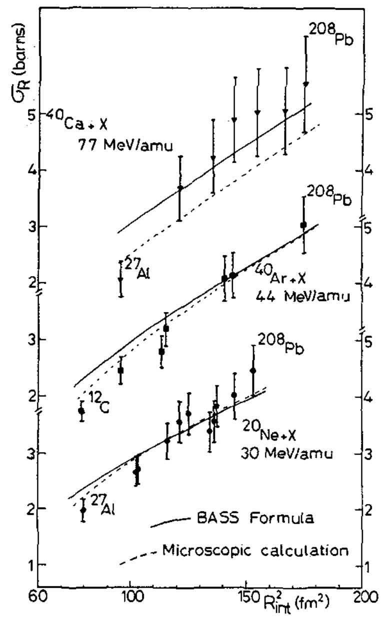


Fig. 13 - Experimental σ_R data and theoretical calculations in the BASS and KAROL models

The large sampling of σ_R values obtained with the radiative method has been compared with predictions of BASS model and of KAROL model. The BASS formulation /7/ is expressed through the classical relationship [1] using : (i) an energy independent interaction distance, strictly defined in configuration space as

$R_{int} = R_{1/2}\ (p) + R_{1/2}\ (t) + 3.2$ fm with

$R_{1/2}\ (A) = 1.12\ A^{1/3} - 0.94\ A^{-1/3}$

(ii) a potential energy

$$V(R_{int}) = \frac{ZpZte^2}{R_{int}} - b\ \frac{R_{1/2}(p)\ .\ R_{1/2}(t)}{R_{1/2}(p) + R_{1/2}(t)}$$

the attractive nuclear potential contribution being derived from the liquid drop model (b ≅ 1 MeV.Fm^{-1}). It must be emphasized that the nuclear contribution takes into account surface effects including an asymmetry term R(p) . R(t)./[R(p) + R(t)] to be related to the volume overlap of the colliding nuclei. The experimental σ_R values and results of calculation in the BASS an KAROL models are displayed in Fig. 13. For the heaviest colliding systems the BASS formulation provides a reasonable overall agreement and for the lightest ones the KAROL microscopic calculation gives the best agreement : this observation may be related to the fact that the influence on σ_R values of the transparency phenomenon is greater for the light systems than for the heavy ones /30,31/.

These general conclusions point out some need for an improvement of straight microscopic calculations by taking into account mean field effects, that has been performed by DiGIACOMO et al /23,24,25/ and by TREFZ et al /27/. It will be noted that experimental σ_R data for the reactions induced by 44 MeV/amu ^{40}Ar projectile /4,37/ are in good agreement with the theoretical predictions given in Ref. 27. Furthermore microscopic calculations must intend to reproduce not only σ_R data, but also differential elastic and inelastic diffusion cross section data /37,38,39/, remenbering that some cancellation effects /24,28/ can make the comparison with experimental data somewhat tricky. With regard to heavy colliding systems it is noticeable that Coulomb effect leads to reduce, on the one hand the energy range in which the decrease of σ_R may be observed, and on other hand the importance of this decrease (see Fig. 14 from Ref. /18/.

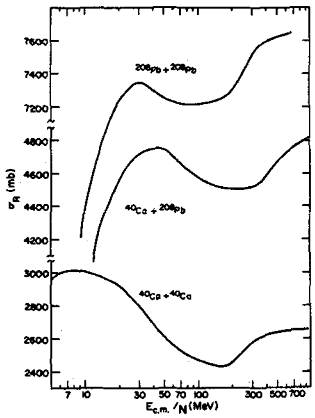


Fig. 14 Microscopic predictions from Ref. / 18/

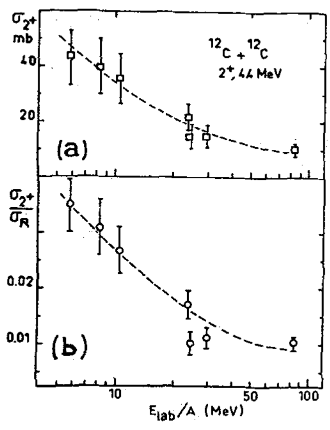


Fig. 15 - Excitation function of the collective 2^+ state of ^{12}C (from Ref. /39/) :
(a) absolute variation σ_{2^+}
(b) relative variation σ_{2^+}/σ_R

The dominance of nucleon-nucleon interactions at medium energy is suggested on the basis of the agreement between microscopic calculations and experimental σ_R data (particularly for light colliding systems). A more direct suggestion of this behavior is furnished by the observation of the decrease of collective states excitation (which take place via mean-field interactions), when increasing incident energy. An illustration of such observation is given in figure 15 (form Ref. 39) which clearly exhibits the absolute and relative decrease of the excitation of the 2^+ (4.4 MeV) state of ^{12}C, observed in ^{12}C + ^{12}C inelastic scattering.

As a last remark, it must be emphasized that in microscopic approach of σ_R calculation, the exact spatial distribution of nucleons is a fundamental ingredient. At some level of sophistication of calculation, it would become relevant to take into account the fact that protons and neutrons densities distributions are different /6,40/. Then the question of a neutron skin effect on σ_R value must be addressed /19,30/ for heavy-ion collisions. Measurements of σ_R performed either with ^{12}C beam on ^{64,66,68}Zn targets /31/, or with ^{20}Ne beam on ^{144,150,154}Sm targets /36/, do not allow to actually conclude in a quantitative way considering the errors bars (see Fig. 16)

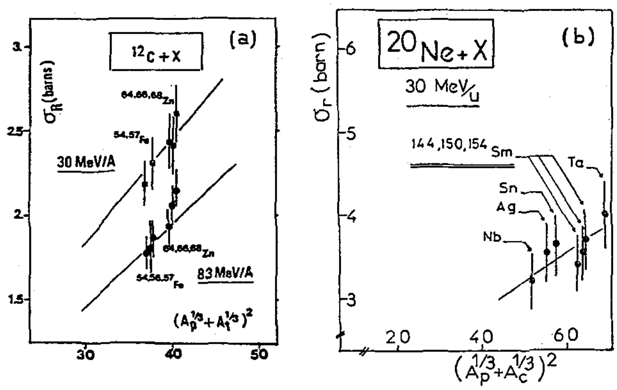


Fig. 16 - Isotopic targets σ_R measurements
(a) with ^{12}C projectile
(b) with ^{20}Ne projectile

IV - SUMMARY AND CONCLUDING REMARKS

In their principles, experimental measurements and theoretical calculations of σ_R are rather simple, but in practice, to obtain very accurate data and perform very fine calculations, we must admit that it is not so easy. We must also be well-advised to derive general conclusions from the present results of heavy-ion σ_R measurements in the Fermi energy range, keeping in mind that σ_R is a global quantity, the variation of which can only give global -but nevertheless fundamental- informations with regard to nuclear collisions, essentially at large impact parameters.

The widely systematic study of σ_R, as a function of the projectile energy, for some light colliding systems /3,5;39/ (e.g. $^{12}C + ^{12}C$) strongly suggests to link the energy dependance of σ_R with the behavior of the total free nucleon-nucleon cross sections : this could attest to the dominant role of individual nucleon-nucleon collisions in the Fermi energy domain /41/. For heavier colliding systems, measurements have been performed /4,36/ using various projectiles (^{20}Ne, ^{40}Ar, ^{40}Ca) of different energy, in the framework of a systematic study of σ_R for a wide range of target masses; a reasonable overall agreement is found with the predictions of the standard theory based on the one-dimensional nucleus-nucleus interaction potential, but this does not exclude agreement with microscopic calculations based on "effective" nucleon-nucleon interaction (thus including mean-field effects as Fermi motion and Pauli blocking /27/). Until we get more numerous and more precise experimental data it would be probably hazardous to extrapolate all the conclusions of $^{12}C + ^{12}C$ measurements to a Xe + Pb reaction (e.g.). Nowadays we can only conclude that the respective roles of "mean-field" and "nucleon-nucleon" aspects in a microscopic description of σ_R have to be discussed and clarified taking into account the mass and energy domains of the collision.

The pieces of nuclear matter that we call nuclei (finite many-body systems) have a specific property which is the existence of a natural boundary, namely a diffuse surface the role of which is fundamental in theoretical interpretation of σ_R. Nuclear transparency (in the Fermi energy range) is a phenomenon which occurs essentially in the nuclei overlap regions associated to low matter density : it is thus concerned with the tails of nucleonic distribution, which have approximately the same extent for any nucleus ($A \geqslant 12$), the value of the surface thickness parameter (t 10 - 90%) being more or less equal to 2.2 fm. As a consequence of this surface property, the (energy dependent) "transparent" region has, at a given projectile energy, very roughly the same extent on impact parameter scale whatever the colliding system is considered. It follows that the relative influence of transparency phenomenon on σ_R value is greater for a light system (e.g. C + C) than for a heavy one (e.g. Ar+Pb). For heavy systems the study of (in)elastic diffusion cross-sections may be a complementary or a more convenient way to investigate the energy dependence of the transmission function /37,39/. It must be also mentioned that the reasonable success of the optical limit of the Glauber theory in describing σ_R is probably due to the central role played by the low matter density surface of the nuclei /42/.

Describing the nuclear collision cross sections in a microscopic way is obviously a very ambitious task, but it is an usual challenge for nuclear physicists (who have sometimes succeded in microscopic interpretation of spectroscopic properties of nuclei). The basic feature of such calculations is the evaluation of the effective nucleon-nucleon interaction in nuclear matter under nucleus-nucleus colliding situation. Almost recent theoretical works /25,27/ are, at least, encouraging. But it is very evident that an experimental data improvement is needed to accompany theoretical developments : more measurements with a good accuracy (< 5%) should be undertaken in a "metrological" ("spectroscopy like") way, that does not necessarily imply a very large systematic work. For instance, it would be interesting to perform σ_R measurements for some isotopic series in order to investigate the neutron skin effect. From a more pragmatic point of view, additional σ_R data would be also of interest to check up on the validity domain (mass and energy) of various parametrization formula of σ_R /7,31,43/.

Our final conclusion will be borrowed from Paul ELUARD /44/ : "il nous faut peu de mots pour exprimer l'essentiel, il nous faut tous les mots pour le rendre réel".

ACKNOWLEDGEMENTS

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